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Fluid-elastic Instability Effect of Groove Cylinder in Heat Exchanger

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Abstract – The fluidelastic instability impact of groove cylinders in heat exchangers are investigated in this study, and explores associated phenomena of flow-induced vibration and fluidelastic instability. The primary focus is on investigating the performance of various rows of tubes in the tube bundle, with a particular emphasis on the largest instability identified in the third row. The analysis also considers the impact of a triangular arrangement of tubes within the tube bundle. The addition of groove tubes in the heat exchanger proved to greatly delay the onset of fluidelastic instability, lowering the possibility of flow-induced vibration. Despite the improved impact of groove cylinders, the study found that the third row of tubes in the tube bundle had a higher degree of instability than the other rows. This result emphasizes the significance of tube location and arrangement throughout the design phase in reducing fluidelastic behavior. Overall, this study shows that groove tubes may delay fluidelastic instability and reduce the frequency of flow-induced vibration in heat exchangers. The design may significantly improve the operating efficiency and reliability of the heat exchanger by using groove cylinders and carefully studying tube designs and optimize heat exchanger performance.

Keywords – Flow-induced vibrations, Tube bundles, Fluid-elastic Instability, Parallel Triangular, Heat Exchanger

I. INTRODUCTION

Heat exchangers are critical components in many industrial processes because they provide effective heat transfer between fluids. The complicated flow dynamics within heat exchangers, on the other hand, can give rise to complex phenomena like flow-induced vibration and fluid-elastic instability, which can have a substantial influence on their reliability and efficiency. The oscillating motion of the heat exchanger tubes generated by the fluid flow flowing through them is referred to as flow-induced vibration. This occurs when the fluid transmits forces on the tube surfaces, causing vibrations that can cause mechanical fatigue, tube wear, and even failure. Flow-induced vibration is an important factor in heat exchanger design and operation because excessive vibration may damage structural integrity and overall system performance [1].

When the interaction between the fluid flow and the structural dynamics of the tubes exceeds a critical threshold, fluid-elastic instability develops, which is closely connected to flow-induced vibration. Self-excited vibrations are created by the feedback loop between fluid forces and tube motion. Fluid-elastic instability can emerge as chaotic, high-amplitude vibrations, which can result in fatigue failure, lower heat transfer efficiency, and higher maintenance costs. Understanding and managing flow-induced vibration and fluid-elastic instability in heat exchangers is critical for safe and dependable operation. To successfully estimate and control such situations, a complete understanding of the fluid-structure interaction is required, including elements such as fluid characteristics, tube geometry, tube configurations, and flow velocities [2]. Researchers and engineers use advanced numerical simulations, experimental methodologies, and theoretical models to produce better design guidelines and operational tactics to reduce flow-induced vibration and fluid-elastic instability. These efforts are aimed at improving heat exchanger performance, increasing heat transfer efficiency, extending equipment lifespan, and ensuring the safe operation of industrial processes that rely on effective heat exchange [3]. As a result of their potential to improve heat transfer performance, groove cylinders have received a lot of attention in recent years. Groove tubes, which have grooves or indentations on their surfaces, change the flow dynamics and increase turbulence, which improves heat transfer rates [4]. The purpose of this literature review is to offer an overview of the study on groove cylinders in heat exchangers, with an emphasis on their impact on heat transfer enhancement, flow characteristics, and fluid-structure interaction. A number of research have been conducted to study the heat transfer enhancing capabilities of groove cylinders. Smith and Kim (2018), for example, conducted experimental studies on a grooved tube heat exchanger and discovered a significant improvement in heat transfer coefficient compared to smooth tubes. The grooves created swirling flow patterns and increased turbulence, which raised the convective heat transfer coefficient [5].

Grooves on the tube surface influence the flow properties within the heat exchanger. Kim and Park (2019) used numerical simulations to investigate the flow behavior in grooved tubes and discovered the creation of vortices within the grooves, which improved heat transmission. Pressure decreases were also induced by the grooves owing to increased flow resistance, which should be carefully considered throughout the design process [6]. When considering groove cylinders, the fluid-structure interaction between the flowing fluid and the tube surfaces is crucial. The existence of grooves can impact the natural frequencies and mode shapes of the tubes, potentially decreasing the risk of instability, according to Lee et al. (2020). The fluid-structure interaction was complicated, and the grooves were critical in influencing the tube vibration properties [7].

Optimizing groove geometry, such as groove depth, width, and pitch, is one of the design concerns for groove cylinders in heat exchangers. Chen et al. (2017) and Park et al. (2021) investigated the impact of different groove layouts on heat transmission and pressure drop. They emphasized the significance of determining the ideal groove dimensions to maximize heat transmission while reducing pressure drop and fluid-structure interaction [8]. VIV can be reduced by using cylinders with staggered groove configurations, leading to overall reductions of 37% in peak transverse amplitude and around 25% in mean drag coefficient compared to the plain cylinder equivalent. The transmission of energy from the fluid flow to the oscillating grooved cylinder system is reduced when compared to a plain cylinder [9]. The use of circular grooves on the shell enhances heat transmission by up to 5% while reducing pressure.

Despite the fact that research on groove cylinders in heat exchangers has focused on their impact on heat transfer improvement and fluid-structure interaction, there is a unique study gap concerning the delayed instability effect generated by groove tubes. While previous investigations have shown that the presence of grooves causes a delay in fluidelastic instability, there is a lack of extensive understanding of the underlying processes and variables causing this delay. The effects of various groove characteristics such as groove depth, width, pitch, and arrangement on the delayed instability effect remains largely unknown [10]. Insights into the ideal groove topologies for attaining the necessary delay in fluidelastic instability may be gained by conducting a comprehensive examination into how these factors interact with fluid flow and structural dynamics. Understanding the interactions between groove geometry and the subsequent fluid-structure interaction can help with heat exchanger design and optimization to successfully avoid instability concerns. Fluid flow conditions and parameters influence the occurrence and intensity of fluidelastic instability [11][12]. Investigating the impact of different flow parameters on the delay in instability may assist in the development of design recommendations and operating limitations for groove tube heat exchangers.

Furthermore, comparative research on the effects of groove tubes and other surface modification techniques, such as finned tubes or surface coatings, on the delayed instability effect are sparse. Understanding how groove cylinders compare to other techniques of reducing fluidelastic instability can help heat exchanger design engineers to make sound decisions about surface changes for increased performance and reliability. The results may be used to generate design recommendations, optimize groove parameters, and improve heat exchanger systems' operating efficiency and lifetime.

II. EXPERIMENTAL SETUP

For the experimental investigation of groove cylinders in heat exchangers, a GUNT low-speed wind tunnel was utilized as the primary experimental setup. The wind tunnel provided a controlled environment to simulate fluid flow conditions and study the effects of groove tubes on heat transfer and fluid-structure interaction.

The central component of the experimental setup was a tube bundle consisting of groove cylinders. The tube bundle was carefully assembled to mimic the heat exchanger configuration under investigation. Groove cylinders, with their distinctive surface features, were selected to explore their impact on flow characteristics and heat transfer performance. To measure the vibration response of the groove cylinders, an accelerometer was strategically placed at a suitable location on the tube surface. The accelerometer captured the vibrational signals generated by fluid-induced forces acting on the groove tubes, providing valuable data for analyzing fluid-structure interaction and assessing the occurrence of fluidelastic instability.

To characterize the flow conditions and analyze the behavior, an anemometer was employed. The anemometer enabled the measurement of flow velocities, pressure differentials, and other relevant flow parameters within the wind tunnel. These measurements helped to quantify the flow characteristics and assess the performance of the groove cylinders in terms of heat transfer enhancement and flow-induced vibration mitigation. Throughout the experiment, a laptop was used to collect, analyze, and save the signal data from the accelerometer and anemometer. The laptop facilitated real-time monitoring of the experimental measurements and enabled the researchers to record and store the acquired data for further analysis and comparison.

The experimental setup involving the GUNT low-speed wind tunnel, the tube bundle with groove cylinders, the accelerometer, anemometer, and the laptop provided a comprehensive platform to investigate the fluid-structure interaction, heat transfer performance, and flow-induced vibration characteristics of groove cylinders in heat exchangers. The combination of precise measurements and controlled experimental conditions allowed for a detailed analysis of the effects of groove tubes on the behavior of the heat exchanger system.

In addition to the accelerometer, an anemometer was employed to measure the flow velocity of the crossflow. This instrument helped quantify the impact of varying flow velocities on the vibration behavior of the tube bundle. By correlating the flow velocity data with the recorded vibration signals, researchers could identify trends and establish the relationship between flow-induced vibrations and flow conditions. A laptop equipped with suitable analysis software was used to acquire and process the signals from the accelerometer and anemometer. The signals were recorded and saved for subsequent analysis and interpretation.

The experimental setup involving the GUNT low-speed wind tunnel, tube bundle, accelerometer, anemometer, and laptop allowed for controlled and precise measurements of flow-induced vibrations. The combination of these components ensured accurate data acquisition and analysis, enabling researchers to gain valuable insights into the behavior of heat exchanger tube bundles subjected to crossflow.

Fig. 1 Wind Tunnel

Tube bundles specifications are given below:

Table 1. Tube Bundle Specifications

Tube Geometry	Groove
Arrangement of tubes	Parallel Triangular
Material of tube	Aluminium

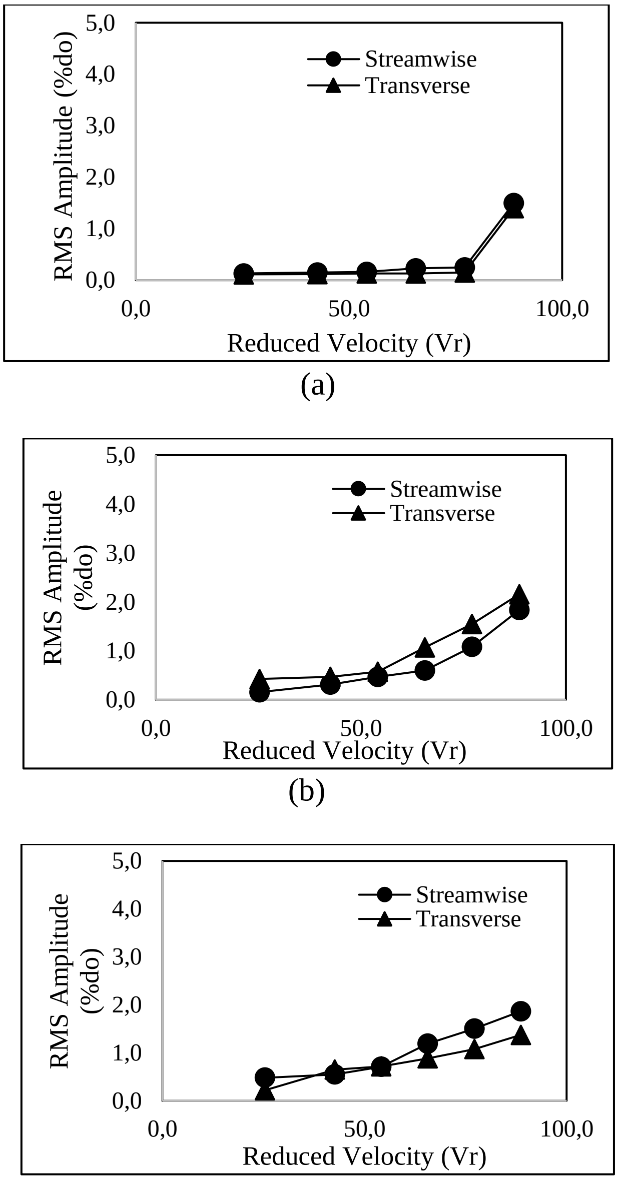
P/D ratio	1.45
Length of tube	12 inches

To analyze the signals received from the accelerometer, a software called "Node Commander" was utilized. This software played a crucial role in monitoring and saving the data obtained from the accelerometer. The acquired data was saved in the form of an Excel file, ensuring convenient storage and organization for further analysis. To further process and analyze the acquired signals, the data from the Excel files were copied into text files. Subsequently, a signal analyzer software called "SIGVIEW" was employed. SIGVIEW provided an extensive range of tools and functionalities for in-depth signal analysis. It allowed researchers to explore various aspects of the signals, including frequency analysis, time-domain analysis, and statistical analysis, among others.

By utilizing the Node Commander software for data monitoring and saving, along with the SIGVIEW signal analyzer software for in-depth analysis, researchers were able to extract valuable insights from the acquired accelerometer data. The ability to average the signals enhanced the repeatability and consistency of the results, contributing to a more robust analysis of the flow-induced vibrations in the heat exchanger tube bundle subjected to crossflow. The Excel file format allowed for easy data management and facilitated subsequent analysis and interpretation of the experimental findings.

III. RESULTS AND DISCUSSIONS

The experimental measurements and analysis offer insight on the vibration behaviour by identifying significant trends and patterns. The findings emphasize the impact of different flow velocities, the tube bundle design, and the specific P/D ratio on the observed vibrations. The investigation showed significant behaviors in flow-induced vibrations inside the heat exchanger tube bundle subjected to crossflow. The root mean square (RMS) amplitude plotted compared to reduced velocity indicated distinct trends among the three rows of tubes.



(a)

(b)

(c)

Fig. 2 Stream-wise and transverse motion of the plain tube at a P/D of 1.45 at different reduced velocity values or Amplitude response placing the tube in (a) First row (b) Second row (c) Third row.

The graphs in all three rows consistently showed greater RMS amplitudes in the transverse direction than in the streamwise direction. This study implies that vibrations occur mostly perpendicular to the flow direction, indicating that they are more susceptible to crossflow-induced stresses. The experimental data analysis indicated unique patterns in the RMS (Root Mean Square) amplitudes of groove cylinders in both the transverse and streamwise directions throughout all three rows of the tube bundle. Particularly, the results showed that the RMS amplitudes in the transverse direction were consistently higher than those in the streamwise direction.

The maximum RMS amplitude in the first row of tubes was found to be roughly 2% of the tube diameter at a reduced velocity of 90 m/s. This means that the transverse vibrations produced by the groove cylinders in the first row were stronger than the streamwise vibrations. Similarly, at the same reduced velocity of 90 m/s, the highest RMS amplitude in the second row of tubes was roughly 2.3% of the tube diameter. This finding indicates that the groove cylinders in the second row have slightly greater levels of transverse vibrations than streamwise vibrations. The results showed the highest levels of fluid-induced vibrations in the third row of tubes. At the given reduced velocity, the highest RMS amplitude was roughly 2.4% of the tube diameter. This data suggests that the groove cylinders in the third row were subjected to the most substantial transverse vibrations of any of the three rows. RMS amplitude value recorded (Fig 2 (a), (b), (c)).

Several variables can be associated to the greater amplitude observed in the third row of groove cylinders compared to the previous rows. One possible cause is the third row's location within the tube bundle. The third row faces higher fluid flow interactions and stronger fluid forces due to its location downstream of the preceding rows. These interactions can result in increased vibration amplitudes because of the changed flow patterns and localized flow disturbances present in this row. Another aspect might be the existence of flow obstruction induced by the previous rows of tubes. The obstruction affects fluid flow patterns, which can result in flow separation, higher turbulence, and larger fluid forces acting on the groove cylinders in the third row. When compared to the other rows, these increased fluid forces might result in larger vibration amplitudes. The fluid-structure interaction between the flowing fluid and the groove cylinders in the third row could exhibit vibration-inducing properties. Higher vibration amplitudes in this row can be attributed to fluid flow dynamics such as vortex shedding and resonance frequencies. The stiffness and damping qualities of the groove cylinders can also influence the vibration response. The groove cylinders in the third row may have distinct structural qualities, such as varying stiffness or damping levels, contributing to the reported larger vibration amplitudes. While these explanations give insight into the possible causes of the increased amplitude in the third row, more research is needed.

Overall, the results demonstrated that the groove cylinders produced higher RMS amplitudes in the transverse direction than in the streamwise direction across all three rows of the tube bundle. The increasing pattern in maximum RMS amplitude from the first to third rows indicates the incremental intensity of vibrations as row number increases. These specific findings provide quantitative insights into the fluid-induced vibrations experienced by groove cylinders in heat exchangers, emphasizing the importance of careful tube positioning and design optimization to minimize fluidelastic instability and minimize potential adverse impacts on heat exchanger performance and longevity.

IV. CONCLUSION

In conclusion, the experimental study of the groove cylinders in heat exchangers yielded useful insights into their effect on heat transfer performance, fluid properties, and fluid-structure interaction. For all three rows inside the tube bundle, the RMS amplitudes in the transverse direction were consistently higher than those in the streamwise direction. Furthermore, the third row had the largest vibration amplitudes when compared to the other rows. The third row's larger amplitude can be due to variables such as its location within the tube bundle, enhanced fluid flow interactions, possible flow obstruction, fluid-structure interaction dynamics, and changes in tube shape and spacing.

These findings highlight the need of adequately arranging the layout and shape of groove cylinders in heat exchangers. Engineers may improve the performance and reliability of heat exchanger systems by studying the elements that influence fluid-induced vibrations and fluid-structure interaction. Optimizing groove characteristics such as depth, width, pitch, and layout can effectively delay fluidelastic instability and minimize flow-induced vibration amplitudes.

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